长期生态学研究引领中国沙区的生态重建与恢复*

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摘要　长期生态学研究揭示了干旱沙区土壤水循环的植被调控机理，解决了降水小于200 mm沙区植被建设的关键技术，提出了生态恢复的技术体系及其应用模式；引领了荒漠生物土壤结皮的研究，探明了人工植被稳定性维持的机理，拓展了荒漠系统生态恢复的生态水文学理论基础，推动了干旱逆境生理生态学的研究，在国内外产生了重要影响，为我国风沙危害治理和沙区生态重建与恢复提供了基础理论和技术支撑。

关键词　风沙治理，荒漠生态系统，长期定位监测研究，人工植被，生态水文

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退化系统的恢复和重建是人类生存与可持续发展所面临的严峻挑战。我国的生态退化十分严重，已呈现出由结构性破坏向功能性紊乱演变的发展趋势，退化生态系统面积约占国土总面积的1/4。其中，沙化土地占国土总面积的17.93%，因荒漠化造成的直接经济损失约540亿元/年。新中国成立以来，党和国家十分重视沙化土地的治理和沙区生态重建工作。自2000年以来，全国荒漠化和沙化土地面积连续3个监测期保持“双减少”，沙化土地面积由20世纪末年均扩展3 436 km^2转变为目前的年均缩减1 980 km^2，实现了由“沙进人退”到“人进沙退”的历史性转变。2015年中央出台的《关于加快推进生态文明建设的意见》中明确提出，到2020年我国50%以上可治理的沙化土地要得到有效治理。中科院沙坡头沙漠试验站作为我国最早建立的沙漠研究治理生态站，60余年的长期生态学研究为沙化土地治理和沙区生态重建与恢复提供了重要理论和技术支撑，为中国的防沙治沙作出了贡献。

1 解决了降水小于200 mm的干旱沙漠地区植被建设的关键技术，证实了区域生态恢复的可行性

在成功地解决了包兰铁路沿线流动沙丘固定的基础上，对干旱沙漠地区无灌溉人工植被建立的理论范式和技术体系进行了长期的定位研究。明确了以建立覆盖度小于15%的旱

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生灌木为主的植被恢复体系是草原化荒漠沙区生态系统恢复的最佳模式。发现固沙植被建立初期，旱生灌木和沙障有效地减轻了沙面的强烈风蚀，确保了沙面物理环境的稳定，使大气降尘和养分在沙面沉积，为草本植物的定居和繁衍创造了适宜的生境，隐花植物的拓殖使植被系统更为稳定。原来群落结构单一的植被演变成复杂的多层片结构和多功能群的植被。固定沙丘生物多样性的恢复使原有的人工固沙植被系统演变成与同一气候带相似的、稳定的荒漠生态系统。长期生态学监测研究证实了在我国沙区通过人工植被建设实现区域生态恢复是可行的（图1），为全球干旱区沙害治理提供了范式[1-5]。

2 揭示了干旱沙区土壤水循环的植被调控机理，为通过人工植被建设实现生态修复提供了理论支撑

揭示了干旱沙区人工固沙植被在种类组成、结构和功能群等生态系统特征方面对沙地水循环演变的响应机理和演替规律[1,5]；对沙区植被调控水循环和水循环驱动植被演替过程进行了参数化和量化研究（图2），对植物水分利用计算实现了尺度转换，量化了植被与土壤水分之间的动态关系[6-12]；明确了水循环对土壤-植被系统演替的驱动作用，定量确定了水分在土壤-植被系统中的再分配机制，探明了荒漠生态系统地表径流驱动下的水分再分配机理，研究了植物蒸腾特征及其尺度转换，揭示了固沙灌木冠层截留特征，探明了固沙灌木树干液流规律，定量研究了沙区稀释凝结水特征及对环境因子的响应规律，建立了土壤水分随机模型，确定了不同生物气候带植物固沙的生态-水文阈值。基于水分和其他生境因子异质性的长期动态变化，提出了干旱沙区植被恢复的模式[4,5]；回答了干旱沙区植被-土壤系统中水分及生境因子恢复的速率、恢复时间等生态恢复特性的问题[13]。理论上解释了沙地土壤水分有效性浅层化与植被向荒漠化草原演变的格局特征[4]，阐明了生态恢复过程生物多样性的繁衍与水循环关系及其适应性对策的生态学机理[1,4]，为干旱沙区通过建立人工植被促进生态恢复提供了理论支撑（图3）。提出生态修复的关键技术和模式，并在实践中广泛应用推广。包括沙区雨养型植被建设技术与模式、新型飞播植被技术与模式、沙区交通干线“灌木+草本+隐花植物”立体生态恢复技术和植物水分生态位造林技术[3-14]。

图 1　沙坡头无灌溉人工植被防护体系说明合理的植被建设促进了区域生态恢复

3 理论上阐明了固沙植被稳定性维持的生态学机理，提出了荒漠生态恢复的理论模式

长期监测表明，随着固沙植被区深层土壤的干旱化，灌木种在群落中的优势地位和主导作用也逐渐减弱，并有从植被组成中退出的趋势。此过程因灌木“沃岛效应”的削弱而相应地使土壤资源分布的空间异质性程度减弱。大量固定沙面的隐花植物（藻类、藓类和地衣）的繁衍、一年生植物和多年生草本的定居，使植被朝着以草本为优势的、与邻近草原化荒漠和荒漠化草原类似的原生植被类型演变和恢复。因此，土壤资源分布的异质性程度在植被格局和过程中起着重要的作用，也是驱动干旱区植被退化或恢复的关键因素之一，而土壤生境的恢复则决定着生态恢复效果的可持续性[2,15,16]。当土壤资源异质性程度高时，系统发生退化，当异质性降低时，系统开始恢复[15]。

图 2　利用大型称重式 Lysimeter 研究干旱沙区土壤水循环的植被调控机理

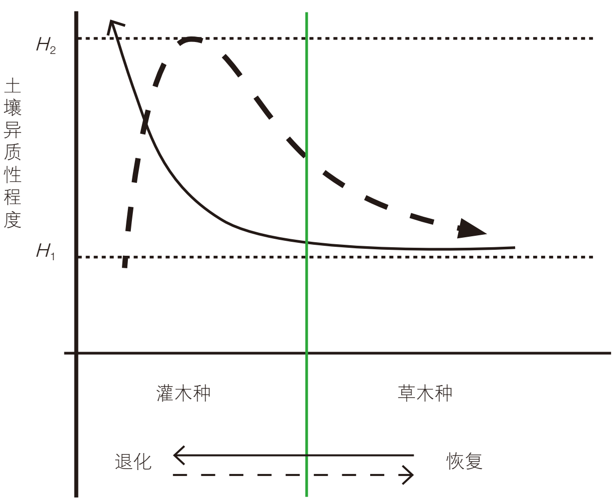

图 3　荒漠生态系统恢复的理论模式

4 探明了生物土壤结皮的生态与水文功能

生物土壤结皮（Biological Soil Crust, 以下简称 BSC）是由隐花植物如蓝藻、绿藻、地衣、藓类和微生物，以及相关的其他生物体通过菌丝体、假根和分泌物等与表层土壤颗粒“胶结”而形成的，具有独特结构和功能的地表生物覆盖体，是荒漠系统中联结生物与非生物因素的“生态系统工程师”，其盖度达到干旱区地表活体覆盖的 40% 以上。基于野外长期定位监测，通过控制与模拟实验，率先揭示了温带荒漠 BSC 的形成和演替规律，提出了大气降尘是其形成物质基础的重要观点，明确了 BSC 的演替分为蓝藻、地衣和藓类为优势类群的 3 个阶段（图4），为甄别干旱区生态退化或恢复提供了新途径，为全球荒漠化防治和风沙区生态重建提供了新思路[1,5,17,18]；阐明了 BSC 对降水入渗、地表蒸发、凝结水捕获和土壤水再分配等水文过程的影响机制[17,19-21]；提出了 BSC 拓殖驱动了沙区人工植被演替的新观点[17]，揭示了 BSC 对维管植物种子萌发、定居和存活的影响机制[22]，认为 BSC 通过改变土壤水文过程和影响植物的存活驱动了植被的演替，理论解释了我国沙区部分人工植被退化的机理[17]；揭示了 BSC 碳、氮固定的生理生态学机制，提出并实验证明了 BSC 是温带荒漠生态系统碳、氮来源的重要贡献者的观点，为荒漠系统碳、氮来源提供了新的证据[23-25]；实验证明了 BSC 对土壤动物活动的影响，以及 BSC 对气候变化与环境干扰的响应，包括 UV-B 辐射、氮沉降、风沙流和沙埋干扰，以及生态系统管理措施和人为干扰的响应[17,26]。出版了《荒漠生物土壤结皮生态水文学研究》和《中国沙区生物土壤结皮生态生理学研究》专著 2 部，引领了国内相关研究[27,28]。

5 探讨了极端环境下植物抗逆的分子生物学机制

在植物逆境适应的分子机理研究方面，首次在单子叶植物中发现了与植物抗旱密切相关的角质层基

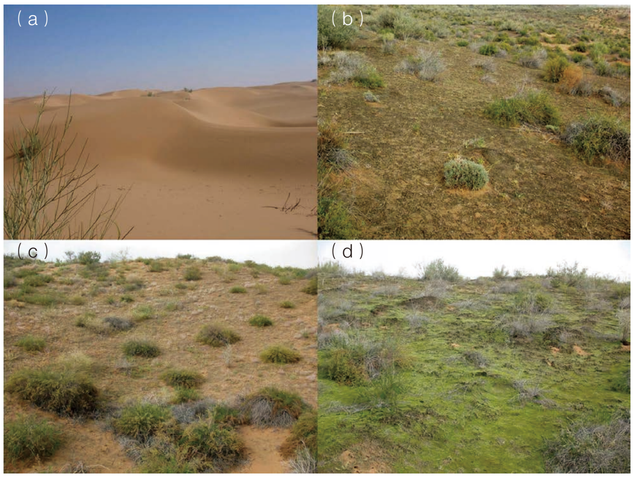

图 4　生物土壤结皮演替顺序

（a）腾格里沙漠流动沙丘；（b）以蓝细菌和藻类为优势种的生物土壤结皮；（c）以地衣为优势种的生物土壤结皮；（d）以藓类为优势种的生物土壤结皮

因 *Eibi1*，该基因与叶片角质层保水功能密切相关（图5）。研究了叶片角质层形成机制与角质层保水功能对植物抗旱的贡献[29,30]。分析了荒漠植物抗逆适应的基因调控机制。通过转录组学发现沙米中有大量耐热基因和丰富的热激蛋白，且高温胁迫能够诱导这些基因的快速高度表达，同时发现沙米具有很好的耐盐性[31]。红砂转录组学研究显示红砂中存在与3种抗旱适应机制（逃旱、避旱和耐旱）相关的大量基因，同时发现次生代谢黄酮类合成代谢途径和 C_4 光合代谢途径参与了干旱适应调控[32]。数字基因表达谱分析了不同胁迫处理后红砂差异表达基因及其变化，发现促分裂原活化蛋白（MAP）激酶级联信号途径和黄酮合成代谢途径相互作用参与对非生物胁迫的调控[33-36]。

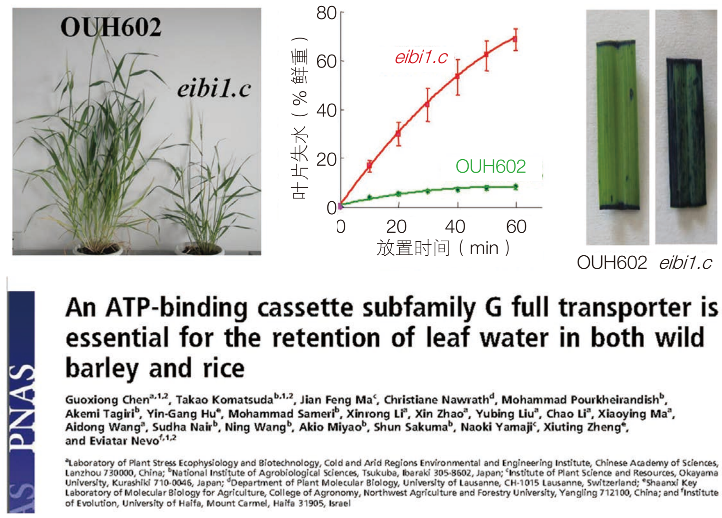

图5　角质层 *Eibi1* 基因与叶片角质层保水功能研究的相关结果发表在 *PNAS*

在植物逆境适应的生理机制方面，发现荒漠植物在非生物胁迫过程中体内能够累积大量的渗透调节物质，维持细胞膨压并降低细胞内的渗透势，同时具有大量的抗氧化物质来有效清除体内活性氧自由基的伤害。另外，荒漠植物叶片表皮超微形态结构和叶肉内部结构表现出丰富的多样性，表皮附属物（如绒毛、蜡质层等）与旱生结构相互协调，共同抵御强光以及降低蒸腾和细胞渗透势等来适应干旱和其他不利环境[37]。不同生境下植物还形成不同的适应类型，如不同生态型芦苇从表型到结构都进化出不同的适应机制[38]；胡杨叶片在发育过程中形成不同的叶型，成熟的阔叶型具有最强适应能力[39]。荒漠植物还具有强大的代谢调控能力。水分代谢过程中通过增大根部导水率而形成较低的水势，同时通过木质部栓塞而阻断高强度的蒸腾来应对干旱环境[40]。另外，C_4 代谢途径在荒漠植物中也发挥了重要作用。

6 结语

60年来，沙坡头站始终围绕国家生态建设的重大科技需求和国际长期生态学学科发展的需要，在沙害防治和荒漠生态系统恢复与重建等方面取得了一大批公益性的原创性成果，解决了国家在沙漠和沙漠化土地治理中亟需解决的科技问题，为区域经济与社会可持续发展提供了重要的科技支撑。先后获得中科院科技进步奖一等奖、国家科技进步奖特等奖、联合国开发计划署（UNEP）“全球环境500佳”、UNDP“荒漠化防治最佳实践奖”、宁夏回族自治区科技进步奖一等奖、甘肃省自然科学奖一等奖、国家科技进步奖二等奖等多项国家和省部级奖励。自2000年以来，在国际知名刊物发表 *SCI* 论文300余篇（含 *PNAS* 3篇），出版专著8部，在国内外产生了重要的影响。我们坚信，沙坡头站的长期生态学研究仍将在我国北方风沙区生态恢复与生态安全的实践中继续发挥理论指导与技术支撑的重要作用。

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Long-term Ecological Research Guides Ecological Restoration and Recovery in Sandy Areas of Northern China

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Abstract In more than 60 years since the foundation of Shapotou Desert Research and Experiment Station (SDRES) of Chinese Academy of Sciences, SDRES has been committing itself to serving the national needs, and made important progresses in the realms of sand hazards control, the reconstruction and restoration of desert ecosystems, eco-hydrology of sandy lands, and drought stress physiology and ecology. SDRES had been awarded the State Science and Technology Advancement Prize for two times (one for the top-class prize, and one for the second-class prize), and won the Best Practice Prize in Combating Desertification by United Nations Development Program. SDRES was also elected to the Global 500 Roll of Honor for Environmental Achievement by the United Nations Environment Program. Long-term ecological research (LTER) in SDRES revealed the vegetative regulation mechanisms within soil water cycle of arid desert areas, developed the key techniques for vegetation construction in desert areas with rainfall < 200 mm, formulated the technique system and application paradigm for ecological restoration, clarified the mechanisms in maintaining stability of artificial revegetation, broadened the eco-hydrological theoretical basis of ecological restoration within desert ecosystems, promoted the studies in drought stress physiology and ecology, and is leading the studies associated to desert biological soil crusts. Long-term ecological research (LTER) in SDRES had also made great influences both at home and abroad, provided the basic theory and technique support for combating wind and sand hazards and for the ecological reconstruction and restoration in sandy lands of China, and had made a great contribution to China's practices in sand prevention and control.

Keywords sandy erosion control, desert ecosystems, long-term monitoring and research, artificial vegetation, ecohydrology

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